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Computational and experimental analysis of supersonic air ejector: Turbulence modeling and assessment of 3D effects

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ABSTRACT

Numerical and experimental analyses are performed on a supersonic air ejector to evaluate the effectiveness of commonly-used computational techniques when predicting ejector flow characteristics. Three series of experimental curves at different operating conditions are compared with 2D and 3D simulations using RANS, steady, wall-resolved models. Four different turbulence models are tested: k–ε, k–ε realizable, k–ω SST, and the stress–ω Reynolds Stress Model. An extensive analysis is performed to interpret the differences between numerical and experimental results. The results show that while differences between turbulence models are typically small with respect to the prediction of global parameters such as ejector inlet mass flow rates and Mass Entrainment Ratio (MER), the k–ω SST model generally performs best whereas ε-based models are more accurate at low motive pressures. Good agreement is found across all 2D and 3D models at on-design conditions. However, prediction at off-design conditions is only acceptable with 3D models, making 3D simulations mandatory to correctly predict the critical pressure and achieve reasonable results at off-design conditions. This may partly depend on the specific geometry under consideration, which in the present study has a rectangular cross section with low aspect ratio.

1. Introduction

Supersonic ejectors have long been used as passive pumping devices for a range of applications such as nuclear reactor cooling, pumping of volatile fluids, and compression of refrigerants in energy systems. Superior ejector performance is typically achieved when maximizing the entrainment of a low pressure stream (suction flow) with respect to a certain amount of high pressure flow (motive flow), or in other words, by maximizing the Mass Entrainment Ratio (MER) defined as

$$\mathrm{MER} = \frac{\dot{m}_{suction}}{\dot{m}_{motive}} \qquad (1)$$

This entrainment effect is the result of momentum transfer between two fluids through a shear-mixing layer inside the ejector, depicted qualitatively in Fig. 1. A high pressure motive flow enters a converging–diverging nozzle where it chokes at the throat and then accelerates to supersonic velocities in the divergent section. The low pressure stream enters the suction nozzle, accelerates slightly, and then reaches the mixing chamber. At this point, mechanical energy is transferred from the supersonic motive stream to the subsonic suction stream through the development of a turbulent mixing layer. Depending on the geometric design and operating conditions, the resulting mixed stream may reach supersonic conditions before exiting the mixing section. The supersonic mixed flow will then adjust to pressure conditions in a succession of oblique shocks (Matsuo et al., 1999). The position of the shock train depends on the back pressure, where the higher the outlet pressure, the earlier the mixed flow will shock (for very low back pressure, the shock train enters the subsonic diffuser). Downstream of this point, the motive jet becomes subsonic and the pressure increases gradually to the outlet pressure. Under these circumstances (where the suction flow reaches or exceeds sonic velocity), ejector operation is said to be “on-design,” and the suction flow rate is independent of the outlet pressure. On the contrary, if the mixed flow remains subsonic, the amount of suction flow drawn into the ejector depends on the outlet pressure and the operation is said to be “off-design.” The threshold value of outlet pressure between these two operational modes is called the “critical pressure.” Fig. 2 shows a characteristic curve of the ejector, generated at a constant motive and

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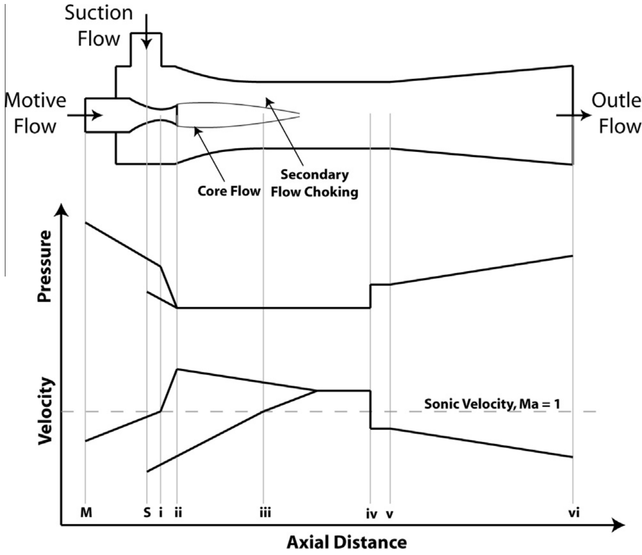

Fig. 1. Schematic of ejector with corresponding qualitative pressure and velocity profiles.

suction inlet pressure, and varying outlet pressure. The critical point is indicated at the critical pressure where the transition between on- and off-design modes occurs.

2. Prior work

The global behavior described above is the result of a combination of complex flow features inside the ejector including boundary layers subject to adverse pressure gradients, turbulent mixing layers bounded by near-wall regions, compressibility effects like shock-induced separations, vortex shedding, and recirculating regions. It is because of this complexity that ejector designs and performances have thus far been difficult to characterize and optimize. With the advent of modern computational techniques, new tools for analyzing such flows have become available to overcome the difficulties in predicting ejector flow. However, they are still far from being completely reliable, making experimental validation necessary. Previous studies (Bartosiewicz et al., 2005, 2006; Hemidi et al., 2009a, 2009b) have highlighted the sensitivity of CFD results to the turbulence model used, and no general agreement has been found as to which turbulence models are best for modeling ejector flows. Several authors have shown that discrepancies between CFD and experiments are strongly related to operating conditions (Bartosiewicz et al., 2006; Sriveerakul et al., 2007). In particular, it was found that the prediction of MER at off-design conditions is more challenging than at on-design conditions. One way to capture off-design conditions would be to perform more accurate 3D simulations, but very few examples of this can be found in the literature. Pianthong et al. (2007) performed 3D simulations on an axisymmetric geometry and found results similar to those from 2D simulations. However, they evaluated only one pressure profile at on-design conditions without considering off-design conditions. Bouhanguel et al. (2009) also performed 3D axisymmetric simulations with different turbulence models. They compared the results with 2D simulations in the case of zero suction flow and found that 3D calculations were in better agreement with the experimental data.

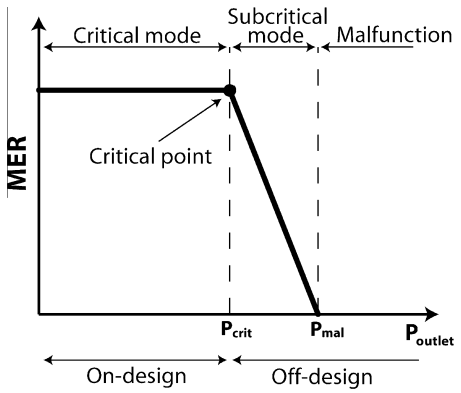

Fig. 2. Qualitative ejector characteristic curve at a set motive and suction inlet pressure. On- and off-design regions are labeled, as well as the critical point at the threshold between these two regions.

The lack of off-design validation studies in the literature, coupled with the limited comparison of different turbulence models, provides the motivation for this study. The present work compares several 3D simulations to equivalent 2D simulations for the rectangular cross-sectional ejector geometry of interest. Furthermore, four different turbulence models are compared to find the scheme that best reproduces experimental results. This comparison takes into account global parameters (MER and mass flow rates) and also includes an investigation of the sources of the discrepancy between numerical and experimental results.

3. Experimental setup

A schematic of the experimental apparatus is provided in Fig. 3. The air supply to the motive nozzle is provided by an industrial Ateliers François compressor (Model CE46B with a capacity of 1320 m^3/h FAD and motor power of 250 kW). Before entering the ejector, the air accumulates inside a reservoir at ambient temperature and a set pressure of 16.0 bar. The motive stream pressure is then regulated down to the desired inlet pressure with a Bellofram T-2000 pneumatic valve. Motive pressures at 2.0, 3.5, and 5.0 bar were tested for comparison with computational results, corresponding to different levels of expansion of the motive flow. The suction flow is taken from the ambient for all tested conditions. The outlet of the ejector also leads to the ambient, and a butterfly valve regulates the exit pressure to the desired set point. For each motive pressure, the outlet pressure is increased incrementally from ambient pressure to produce a full characteristic curve like that shown in Fig. 2.

Fig. 3 shows the locations of pressure, temperature, and mass flow measurements. Temperature measurements are taken using PT100 RTD temperature probes (uncertainty ± 0.5 °C including DAQ error), while pressure measurements are taken using Endress Hauser and Kistler pressure transducers (uncertainty < ±300 Pa). Mass flow rates are determined by measuring the air pressure drop across an orifice plate of known dimensions. The values and uncertainties for these measurements are determined according to ISO standard 5167 (uncertainty generally < ±0.9%). It should be noted that measuring the mass flow rates in this manner introduces pressure losses that change the conditions at the ejector inlets. For this reason, two other pressure transducers are positioned downstream of the motive and suction orifice plates to yield the correct boundary conditions for comparison with CFD results.

The ejector test section itself, shown in Fig. 5, is designed to have undistorted visual access with flat front and back Plexiglas windows. For this reason, the ejector has a planar rather than axisymmetric geometry with a rectangular cross-section. The ejector is designed such that at the given height available for visual access, the depth of the ejector was enough to allow for equivalent motive jet surface area available for momentum transfer when